Optimal Location for a Helicopter in a Rural Trauma System: Prediction using Discrete-Event Computer Simulation

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A discrete-event computer simulation was developed using the C programming language to determine the optimal base location for a trauma system helicopter in Maine, a rural area with unevenly distributed population. Ambulance run reports from a one-year period provided input data on the times and places where major injuries occurred. Data from a statewide trauma registry were used to estimate the percentage of cases which would require trauma center care and the locations of functional trauma centers. Climatic data for this region were used to estimate the likelihood that a helicopter could not fly due to bad weather. The incidence of trauma events was modeled as a nonstationary Poisson process, and location of the events by an empirical distribution. For each simulated event, if the injuries were sufficiently severe, if weather permitted flying, if the occurrence were not within 20 miles of a center or outside the range of the helicopter, and if the helicopter were not already in service, then it was used for transportation. 35 simulated years were run for each of 4 proposed locations for the helicopter base. One of the geographically intermediate locations was shown to produce the most frequent utilization of the helicopter. Discrete-event simulation is a potentially useful tool in planning for emergency medical services systems. Further refinements and validation of predictions may lead to wider utilization.

INTRODUCTION

The optimal placement of emergency vehicles in a given geographic area is a problem in which the techniques of operations research can be usefully applied. Expensive resources must be distributed in such a way that the delivery of emergency services is sufficiently rapid for all possible locations within the area and as rapid as possible for as many events as possible, but with a minimum cost (generally by minimizing the number of vehicles).

If certain (potentially oversimplifying) assumptions are made, some such problems can be solved analytically [1,2,3]. A greater degree of flexibility in modeling a system can be obtained by simulation; this approach has been useful in the evaluation of urban and suburban ambulance locations and performance in Tucson, Arizona [4], Lee County, Alabama [5], and Shanghai, China [6]. However, a simulation model for Emergency Medical Services (EMS) planning in rural areas previously attempted in Maine and elsewhere was unsuccessful because of excessive complexity, failure to involve decision-makers in the modeling process, and other validation failures [7].

Statement of the Problem

In the course of planning for possible helicopter service as part of a trauma system in Maine, we wished to model the use of this expensive resource for transportation of acutely injured patients to designated trauma centers. Specifically, we attempted to predict the optimal location of a single dedicated helicopter within the state, given the probable location of trauma centers, in order to maximize its usefulness for this patient population. A solution is not obvious on inspection, since the majority of the population in Maine is in its southern part, but the largest area is in its central and northeastern parts (Figure 1).

The ideal function of the helicopter is to provide rapid transportation over medium distances from the scene of a serious injury (trauma) or a nearby small hospital to a major hospital with specialized capabilities in the management of severe injuries (a trauma center). In this state, such centers are planned in Portland, Lewiston, and Bangor. Injuries occurring close to these centers can be transported by ground ambulance at least as easily as by helicopter. Injuries occurring far from a helicopter base would take too long or require refueling stops and are therefore impractical for helicopter transport. Of course, only a small percentage of injuries will be serious enough for medical reasons to justify using the helicopter, and specific "launch criteria" must be developed to guide emergency medical

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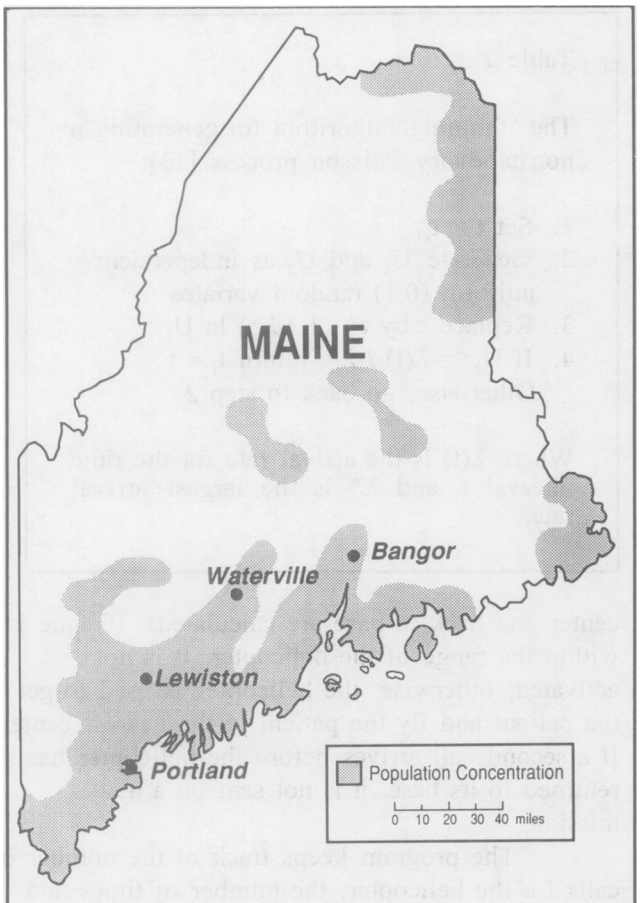

Figure 1: Map of Maine

personnel. Finally, at times a helicopter will be unable to fly because of weather, repairs, or concurrent demands.

Although most of the factors determining the availability and use of a helicopter are beyond human control, one factor which can be altered is the base location of the helicopter, which was the principal interest of our study. Each time it is used, there will be a short delay to get the crew on the helicopter, flight time from base to scene of injury, time spent at scene, flight time from scene to trauma center, time spent at the center, and time to fly back to base and prepare the helicopter and crew for another mission (Figure 2).

The critical times are from notification to arrival at the scene (since the helicopter carries paramedical personnel with higher training than local emergency medical technicians), and particularly the time from notification to arrival at the trauma center (where immediate surgical interventions can be undertaken).

MATERIALS AND METHODS

Computer programming was performed on a DEC computer system using the UNIX operating system. Programs were written in C, with subroutine calls to CSIM, a process-oriented simulation language based upon C [8]. The programs have subsequently been modifed for use with personal computers and DOS. Source code, with comments, is available upon request.

Input data, distributions, sources of randomness, and assumptions

The Maine office of EMS provided the time, date, and town location of all Maine EMS calls during 1991 classified by EMS personnel as "major trauma". The latitude and longitude of all Maine towns was also obtained [9] and entered into a computer file. Combining the location data from these two sources allowed us to plot the location of each incident and determine the frequency of incidents for each town. This empirical distribution was used for the model, which was therefore programmed to return town values randomly in the same frequency as they had occurred in 1991. Flying distances could be easily calculated from the latitude and longitude information.

Occurrence rates varied significantly for different times of day, seasons, and weekends versus weekdays. A nonstationary Poisson process seemed appropriate to model these arrival rates [6]. This resulted in the calculation of 192 average occurrence rates:

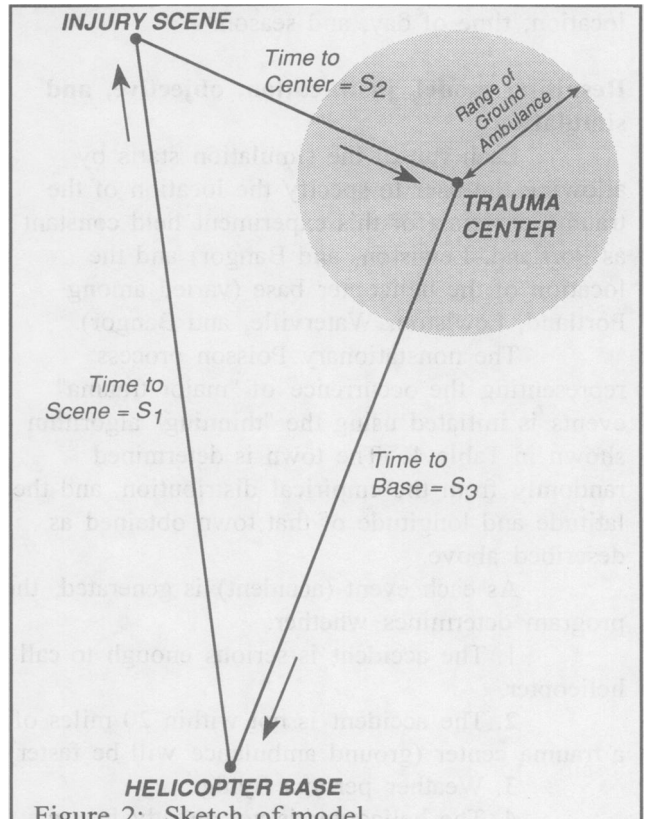

Figure 2: Sketch of model

For example, one rate was used for 6:00 A.M. to 7:00 A.M. for each winter weekend day (Friday, Saturday, or Sunday). A rough estimate of the percentage of "major trauma" calls which would be serious enough to justify the use of a helicopter was obtained, using trauma registry data [10] and based upon experience in other areas [11,12]. The present model assumes that the distributions of times and locations for these most serious injuries are the same as for all injuries classified by EMS as "major trauma".

Estimates of helicopter speed, range, and percentage of time unavailable for mechanical reasons (breakdowns, maintenance, etc.) were obtained from industry sources. Likewise, the time from notification to takeoff, time required at the scene of an accident, time for unloading the patient at a trauma center, and time for refueling and preparing the aircraft for another flight were estimated. In the absence of actual data on helicopter machine and crew performance, these are modeled as constants.

A rough estimate of percentage of time during which a helicopter would be unable to fly due to bad weather was made from data provided by the Northeast Regional Climate Center (Ithaca, N.Y.). We have also made the simplifying assumption that inability to fly because of weather is independent of the occurrence of an accident, location, time of day, and season.

Resulting model, justification, objective, and simulation

Each run of the simulation starts by allowing the user to specify the location of the trauma centers (for this experiment held constant as Portland, Lewiston, and Bangor) and the location of the helicopter base (varied among Portland, Lewiston, Waterville, and Bangor).

The nonstationary Poisson process representing the occurrence of "major trauma" events is initiated using the "thinning" algorithm shown in Table 1. The town is determined randomly from the empirical distribution, and the latitude and longitude of that town obtained as described above.

As each event (accident) is generated, the program determines whether:

1. The accident is serious enough to call helicopter.
2. The accident is not within 20 miles of a trauma center (ground ambulance will be faster).
3. Weather permits flying.
4. The helicopter is not already in use.
5. The helicopter is not being repaired.

If all the above are true, the distances from helicopter base to accident scene to each trauma center and back to base are calculated. If none is within the range of the helicopter, it is not activated; otherwise, the helicopter is used to get the patient and fly the patient to the nearest center. If a second call arrives before the helicopter has returned to its base, it is not sent on a new mission.

Table 1

The "thinning" algorithm for generating a nonstationary Poisson process [13]:

1. Set $t = t_{i-1}$
2. Generate U_1 and U_2 as independent uniform (0,1) random variates
3. Replace t by $t - (1 / \lambda^*) \ln U_1$
4. If $U_2 <= \lambda(t) / \lambda^*$, return $t_i = t$
   Otherwise, go back to step 2

Where $\lambda(t)$ is the arrival rate for the time interval t, and λ^* is the largest arrival rate.

The program keeps track of the number of calls for the helicopter, the number of times and reasons why it was or was not activated, and performance data for each event when it was activated. In addition to those reported here, performance measures included the mean and range of times from call to arrival at the scene of the accident, the mean and range of total times from the call until the patient arrives at the trauma center, and the percentage of the latter times under 60 minutes (the so-called "golden hour" thought to be a critical maximum in trauma management).

Each simulation run consists of one or more simulated years for a given helicopter base with random numbers taken from a single continuous stream. Each simulated year within a simulation run terminates at the end of the year. For this study, 35 years were simulated for each of the four possible helicopter base sites using four different non-overlapping random number streams. Data of interest were produced for each run and compared.

The chief objective, as described above, was to determine the optimal location for the helicopter base, as this is essentially the only factor which can be controlled. If all assumptions are correct, the number of missions flown is the statistic of importance, since it is further presumed that the seriously injured patients not transported by helicopter are at risk for complications or death as a result of the delay. Furthermore, to be financially viable, the helicopter should be given

as many appropriate missions as possible in order to generate revenue, since its costs are largely fixed.

Verification of the program was achieved in several ways: Where possible, functions were written, compiled, and tested as separate entities. Functions were given values for which the results were known, and the known output values were then compared with those produced by the functions for correctness. Each section of code was checked by another member of the project team not involved in writing that section of code. The program was run for a simulated time period of 20 days and the results verified by hand. The effectiveness of the thinning algorithm was verified by obtaining the average number of trauma events for each time interval over 35 simulated years and comparing it (visually) with the input data.

RESULTS

Each simulated year was considered a terminating simulation (so that no "warmup period" was part of the model). A summary of the data is given in Table 2. The decision variable was the mean number of appropriate helicopter missions flown from each base, which ranged from 119 at Portland to 172 at Waterville.

Table 2

POSSIBLE LOCATIONS FOR HELICOPTER BASE

	Por	Lew	Wat	Ban
MISSIONS COMPLETED				
Mean	119.3	157.4	172.1	151.6
S.D.	8.9	12.6	11.9	12.5
TIME TO SCENE (hrs)				
Mean	0.64	0.59	0.56	0.67
TIME TO CENTER (hrs)				
Mean	1.49	1.44	1.42	1.57

Output analysis

From inspection of the results in Table 2, it appears that the most frequent usage of the helicopter occurred when it was based in Waterville. If its planned base in Portland is used as a standard, the mean difference of 52.8 missions is found to be significantly different by one-sided t-test (34 degrees of freedom, $p < .001$).

To select the best of k system configurations (in this case the best of 4 helicopter bases), a standard approach is that of Dudewicz and Dalal [14]: The random variable of interest (in this case the number of helicopter missions per year) is assumed to have a normal distribution for each configuration, but it is not necessary to assume that the variances for different configurations are equal. The problem is formulated such that we want the probability of selecting the best configuration to be greater than a specified value (in this case we choose 95%) provided that we do not care if a configuration is selected whose mean differs from the best configuration by less than a specified value d* (in this case we choose this "indifference amount" to be 10 helicopter missions per year).

Several runs of the simulations are done (at least 20 are recommended; we performed 35), and the sample standard deviations for each configuration are calculated (Table 2). The sample size required for each system i is given by

$$N_i = \max \left\{ n_0+1 \ , \ \left\lceil \frac{h_i^2 S_i^2(n_0)}{(d^*)^2} \right\rceil \right\}$$

where n_0 is the number of runs in this sample, $S_i(n)$ is the sample standard deviation, and d* is the "indifference amount" described above; h_i is a tabulated value, which for n = 35, k = 4, and 95% confidence is approximately 3.02 [13]. The second statistic within the brackets evaluates to less than n_0+1 for all configurations. Thus, the number of runs is sufficient without further replications required for the Dudewicz/Dalal procedure, and we need only choose the configuration with the largest mean, namely basing the helicopter in Waterville.

CONCLUSIONS

Based upon the model described, we have concluded that of the four configurations tested, utilization of the helicopter for transportation of acutely injured patients will be most frequent if the helicopter is based in Waterville. There are, of course, numerous political and other

considerations which would be more difficult to model, such as the possibility of patients transported across state lines, and the costs of maintaining the helicopter and its crew in different locations.

Possible extensions

More realism, at a cost of greater complexity, could be obtained by more detailed estimates of road travel times, either based upon historical data or road distances, and making allowance for the likely scenario of ground transport to a local hospital with subsequent interhospital transfer by air. In order to improve the model further, we would plan to incorporate weather data in the generation of trauma events to avoid the assumption of independence between the occurrence of an injury and the ability of the helicopter to fly. It may be possible to determine the geographic and time distribution only of the most serious injuries, and not simply to assume that they follow the same distribution of all "major trauma" events. Some of the constant times used could be modeled from estimates as triangular distributions or based upon data collected as the system is actually put into use. Although experimentation with a model may be time-consuming, the use of helicopters greatly increases the cost and risk of emergency transportation and it may be difficult to demonstrate a clear net benefit, particularly in areas of low population density [15]. Therefore, we believe the use of sufficiently detailed computer simulation holds considerable promise for helping decisions about helicopter utilization in rural trauma systems.

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